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A METHODOLOGY FOR DETERMINING THE  
ELASTIC CONSTANTS OF IN-SITU ROCKS

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A METHODOLOGY FOR DETERMINING THE  
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ABSTRACT. A methodology for determining the elastic constants by using seismic methods to study the soils during engineering and geological surveys is described.

The determination of elastic constants has an important /201\* place in the study of the rheological properties of rocks. Study of the elastic properties of rocks emerges as an independent task in seismic methods of mineral prospecting, and as a necessary stage in investigations of inelastic properties in problems concerned with statics and dynamics.

So far, a great deal of success has been achieved in studying the elastic properties of rocks by using specimens. A vast body of experimental data has been obtained on the velocities of elastic waves in rocks by using supersonic seismoscopes. But experience shows that soils and rocks change their properties in specimens as compared with their in-situ properties. Research has shown [1] that the velocities of elastic waves depend on isotropic compression, the presence of entrapped air in the soil, the degree to which the soil is saturated with water, and a number of other factors.

The action of all these factors changes drastically when the specimen is brought to day. This fact is indicative of the need to determine elastic constants in situ. One way to do so is to use methods based on recording longitudinal and transverse waves from a natural pulse source. When longitudinal and transverse waves are used, we are in a position to determine the ratios

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\* Numbers in the margin indicate pagination in the foreign text.

$\lambda/\rho$  and  $\mu/\rho$ , where  $\lambda$  and  $\mu$  are the Lamé elastic constants, and  $\rho$  is the density of the rock. The elastic properties can be determined by seismic logging, as well as by using longitudinal and transverse head waves. The concept of using elastic waves to determine Young's modulus,  $E$ , and Poisson's ratio,  $\sigma$ , is not new. There are several papers [4, 5] on investigations such as this, as applicable to engineering geology problems. However, the methodology set forth in this paper differs from that in references [4, 5]. Moreover, this paper discusses how transverse SH waves were generated by an explosion. Attempts to use elastic waves to study Lamé coefficients encounter a number of difficulties associated with the methods used to generate elastic waves, and with the interpretation of the wave picture obtained. This comment applies in particular to transverse waves. It is necessary to generate sufficiently intense transverse SH waves in order to solve these problems. This paper gives examples of the determination of the elastic constants by a seismic method in a cover mass, and in bed rocks. The methodology is reviewed in detail.

#### Determination of the Elastic Constants in Loose Deposits (Rudnyy Altay)

The study of the elastic parameters was made in shotholes (inverse seismic logging), and by surface observations using the refraction waves method and shock action. Control plotting holes, which were drilled to the roof of the basement, were used for 1202 inverse seismic logging (source in the hole, detector on the surface). It is known that small charges placed in a hole generate type SV transverse waves [2], as well as longitudinal waves, when exploded. The explosion of one detonator proved adequate for depths to 60 m. The shot was made from the face of the hole with a 2 m interval, to depths of 10-15 m, and with a 1 m interval at lesser depths. Type SPED-56 seismic detectors were set up 3, 6, 11, and 20 m from the mouth of the hole. Two horizontal detectors and one vertical detector were set up to record the three components,

x, y and z, at each point. Elastic oscillations were recorded /203 by an SS-24-P standard seismometer in the frequency band between 30 and 45 Hz, with the amplitude regulators cut out. Minimum channel amplification was used at depths less than 10-12 m. A system of short (up to 38 m) counter and overtaking travel-time

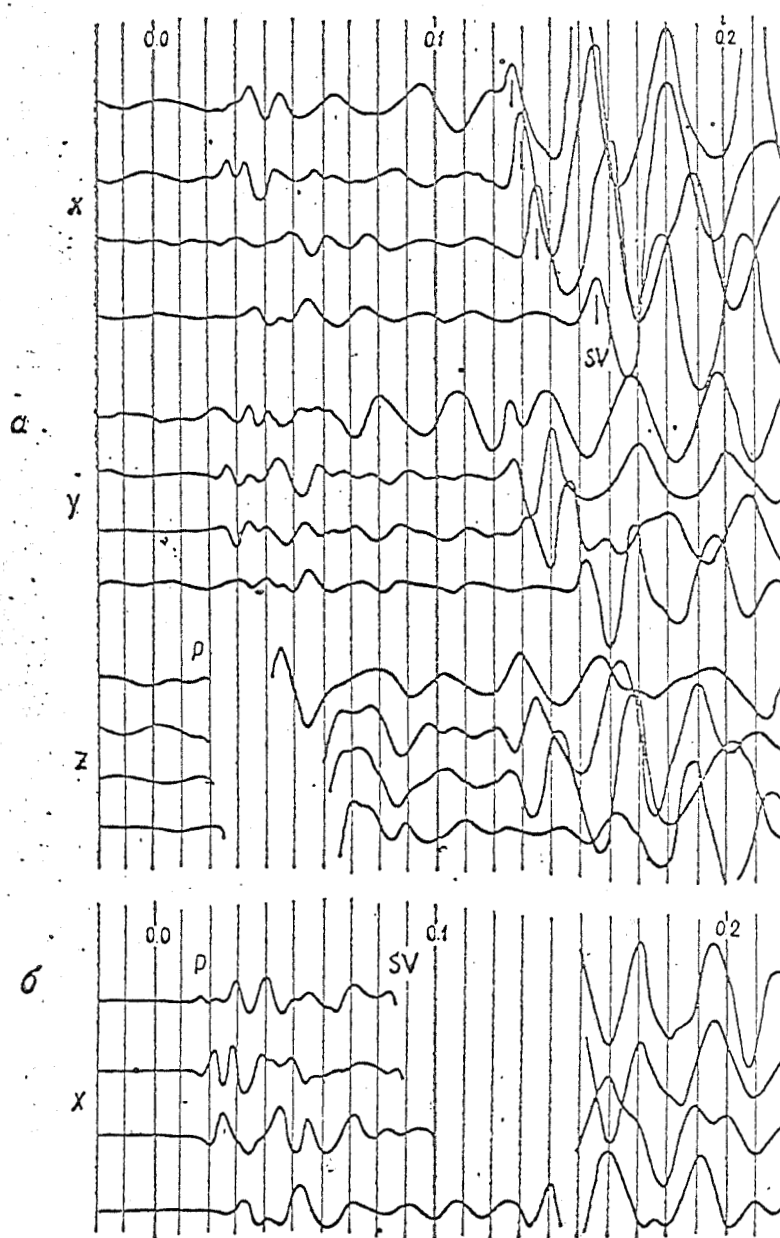


Figure 1. Seismograms illustrating the recording of progressive longitudinal and transverse waves (Rudnyy Altay).

curves (the zone of low velocities for transverse waves) was used to determine the velocities of transverse waves near the day. Horizontal shocks, perpendicular to the line along which the seismic detectors were placed (y-shock), were used to generate transverse waves. The SPED-56 horizontal seismic detectors were oriented perpendicular to the line of the profile (y-reception). The interval between the instruments was between 1 and 2 m. Equipment parameters were the same as those for the hole observations. Maximum channel gain was used for low shock strength (a 10 kg sledge hammer was used). A seismograph was used to record the moment of shock. It was set up beside the wooden billet through which the shock was generated.

Longitudinal and transverse waves were recorded on the seismograms obtained during the hole observations (Figure 1). The vertical instruments record quite clearly the entry of the longitudinal wave. The horizontal components of this wave are small so that the progressive transverse wave can be separated out of their background. It is difficult to separate the transverse wave from the noise background created by the longitudinal wave at shallow depths (the first 6-8 m). The progressive, transverse wave is recorded quite well by the horizontal (x and y) instruments. Clear first entries can be seen on some of the seismograms. As will be seen from the recordings presented, the amplitude of the x-component of the transverse wave is larger than the y-component, and this confirms the conclusions arrived at by N.N. Puzyrev and T.M. Bakharevskaya [2] concerning the generation of SV waves by small explosions in shotholes.

The nonlongitudinal travel-time curves, obtained from the shothole observations were reduced to the vertical, using known methods [3]. Figure 2 shows the vertical travel-time curves /204 for longitudinal and transverse waves, typical of the sedimentary sand and clay strata in the Tushkanikhi region (to the west of Zmeinogorsk). The vertical travel-time curve for the transverse

wave in the upper part of the log (up to 9 m) was constructed from the data obtained from the surface position observations using the refracted wave method. As will be seen from the layer

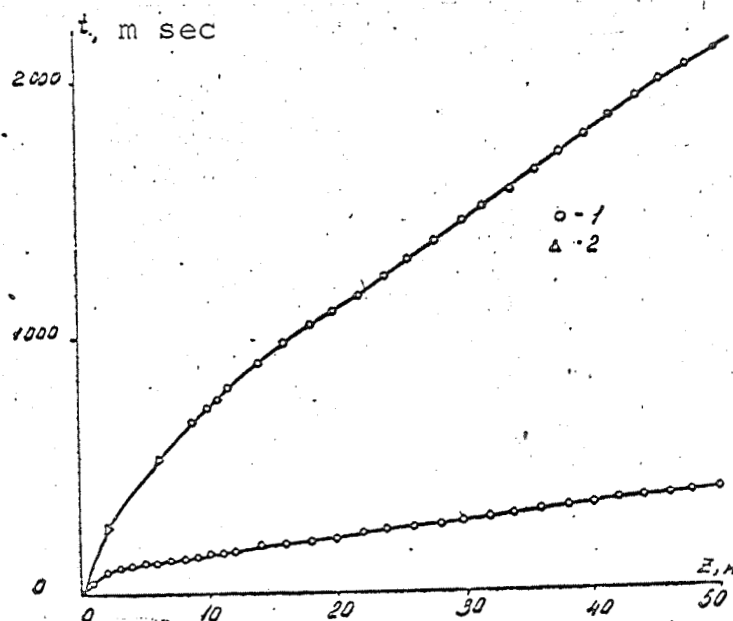


Figure 2. Vertical travel-time curves for longitudinal P and transverse SV waves: 1 - data from inverse seismic logging; 2 - from the results of the study of the low velocity zone.

velocity curves (Figure 2a [sic]), the rate of propagation of the longitudinal, as well as of the transverse waves in the loose stratum increases steadily with depth to its limit, and then remains constant. A satisfactory presentation of the velocity in terms of depth is the approximation

$$V_p(z) = 1,800 - 1,550 e^{-0.15z}$$

for the longitudinal wave, and

$$V_s(z) = 300 - 220 e^{-0.15z}$$

for the transverse wave.

The values for  $V_p$ ,  $V_s$ ,  $\gamma$ ,  $E$  and  $\sigma$  for the sedimentary stratum

in this particular region are listed in Table 1, when

$$\sigma = (2\gamma^2 - 1)/(2\gamma^2 - 2),$$

$$E = V_s^2 \rho [(4\gamma^2 - 3)/(\gamma^2 - 1)],$$

$$\gamma = V_s/V_p.$$

TABLE 1

Depth intervals, m	$V_p$ , m/sec	$V_s$ , m/sec	$\gamma$	Young's modulus, E, in dynes/cm <sup>2</sup>	Poisson's ratio, $\sigma$
0-2	250	80	0.32	$3.7 \times 10^8$	0.443
2-6	1,000	150	0.15	$13.4 \times 10^8$	0.448
6-14	1,330	210	0.165	$26.2 \times 10^8$	0.448
14-60	1,800	300	0.167	$53.5 \times 10^8$	0.486

As will be seen from the table, the Poisson's ratio values for the loose stratum change but little and are not in excess of 0.49. Young's modulus varies over broad limits, depending on depth (by a factor of more than 10 for a change in depth from 2 to 14 m). Densities were not measured in this hole, and the value  $\rho = 2 \text{ g/cm}^3$  was taken as the mean for this particular region on the basis of gravity observations and density determinations made from the specimens.

#### Determination of the Elastic Parameters in the Subjacent Medium

Parametric measurements of the velocities of the longitudinal and transverse waves over short baselines were made in order to determine the elastic parameters of rocks in the subjacent medium.

Short longitudinal profiles, 100 m, were used for parametric observations, with the sources located at the ends of the profile. The selection of this length for the profile was necessitated by 205 measurement accuracy and attenuation of the effective wave.

The distance between the seismic receivers along the profile was selected so that there would be a sure correlation between the effective waves, as well as the accuracy needed to measure seismic velocities. With these considerations in mind, all observations were made on a 10 m interval for longitudinal waves, and on a 5 m interval for transverse waves.

Vertical shock actions (z-shock) were used as the source of longitudinal waves. The transverse waves were generated by horizontal shocks directed perpendicular to the profile (y-shock). Only transverse SH waves are observed in the beam plane in this case. The characteristic indication of SH waves is a phase inversion with a change in the direction of the action.

Shocks causing the generation of longitudinal and transverse waves were created by using a sledge hammer weighing some 10 kg to strike the ground directly, or to strike a wooden billet buried in the ground. Horizontal shocks were produced in two directions in order to verify the inversion in the phase of the SH wave; one was a +y shock, the other a -y shock. A sensor, rigidly fastened to the billet, was used to record the moment of impact. An SPED-56 seismic detector with special, stiffer springs was used as the sensor. Recording the longitudinal (P) and transverse (SH) waves was accomplished using SPM-16 seismic detectors. They were installed vertically (z-reception) and horizontally in a direction perpendicular to the profile (y-reception). Standard equipment, an SS-24-P seismic station, was used.

The longitudinal and transverse waves usually were recorded by 30-45 filtration. It is known that the transverse wave spectrum is much narrower than the longitudinal wave spectrum, and that it is shifted toward the low frequency side. In the case of the observations made in this particular region, the maximum in the spectrum of SH waves is at a frequency between 35 and 40 Hz, and was the reason for the selection of 30-45 filtration as the 206 standard.



Longitudinal, or transverse types of SH waves, direct and head (Figure 3), were recorded, depending on the source and system of short baseline observations used. The basic criteria used to

distinguish the different types of waves were the value of the apparent velocity, and the inversion of the phase of the SH wave under y-shocks of the opposite sign. The sharpest recordings were obtained at the granite and metamorphic schist outcroppings. The visible period of SH waves is approximately 0.02 - 0.03 sec.

Determination of the velocity of the longitudinal and transverse waves was made by using the difference travel-time curve method, and the formula  $V = 2\Delta x / \Delta \Theta$ , where  $\Delta x$  and  $\Delta \Theta$  are the increments of  $x$  and  $\Theta$ , determined from the difference travel-time curve  $\Theta = \tilde{\tau} - \tilde{\tau}$ . The elastic constants were computed using Eq. (1, 2). The results of the parametric measurements are listed in Table 2.

As will be seen from Table 2, Poisson's ratio decreases with an increase in the strength of the rock, approaching a value of 0.25. On the other hand, Young's modulus increases with an increase in the strength of the rock.

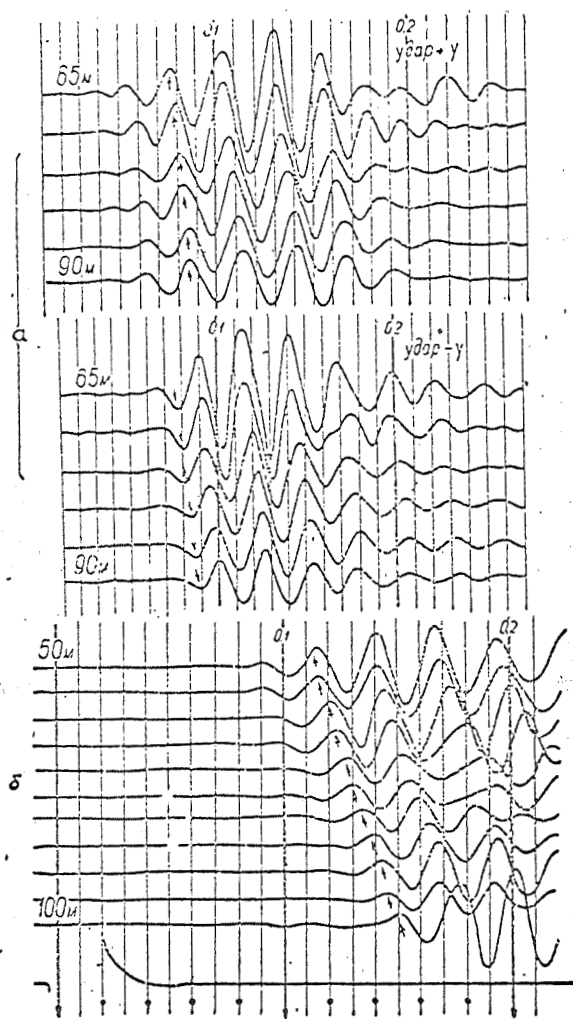


Figure 3. Seismograms illustrating the recording of transverse SH waves (Rudnyy Altay)  
a - inversion of wave phase in the case of y-shocks with opposite sign;  
b - recording characteristic of granite intrusions.

We used the method of generating transverse waves by explo-

TABLE 2

Rocks	Mean $V_p$ , km/sec	Mean $V_s$ , km/sec	Mean $\gamma$	Poisson's ratio, $\sigma$	Density, $\rho$ g/cm <sup>3</sup>	Young's modulus, E dynes/cm <sup>2</sup>
Mesocenozoic loose deposits	1.7	0.29	0.17	0.48	2.0	$0.5 \times 10^{10}$
Devonian igne- ous-sedimentary rocks	2.7	1.3	0.48	0.35	2.65	$12.0 \times 10^{10}$
Metamorphic series, lower Paleozoic	3.0	1.5	0.50	0.33	2.71	$15.4 \times 10^{10}$
Granite intru- sions	2.3	1.3	0.56	0.27	2.60	$9.7 \times 10^{10}$

sions with stemming, developed in the Institute of Geology and Geophysics of the Siberian Branch of the Academy of Sciences of the USSR by N.N. Puzyrev, K.A. Lebedev and G.N. Lebedeva, in addition to shocks. Shock sources had been used to generate type SH waves, but their power was limited and the feasibility of transporting the strikers was limited.

An example of the use of the methodology described is the determination of the elastic constants of crystalline limestones in the vicinity of the Iskiti quarry. The limestones were covered with loose deposits 40 m thick, made up of clays and loams. Longitudinal waves were generated by superposed charges, and the transverse waves were generated by explosions in trenches with dry stemming. A group charge, 3 x 60 g, connected by detonator cord, was used to generate the transverse waves (Figure 4). The velocities of the longitudinal and transverse waves were determined by counter travel-time curves, and the density was found in the laboratory. The following values were obtained:  $V_p = 6,000$  m/sec;  $V_s = 2,730$  m/sec;  $\rho = 2.8$  g/cm<sup>3</sup>;  $\gamma = V_s/V_p = 0.455$ ;  $\sigma = 0.37$ ;  $E = 57.2 \times 10^{10}$  dynes/cm<sup>2</sup>.

The methodology for determining elastic constants by the seismic method described in this article can be recommended for studying soils during engineering and geological surveys, as well as when determining the strength of rocks in planned quarries. The methodology is effective for homogeneous media and for stratified media close to the horizontal in their stratification. It is recommended that shothole observations be combined with the profiled, seismic method that utilizes refracted waves to determine the parameters of a subjacent medium, to study the cover mass.

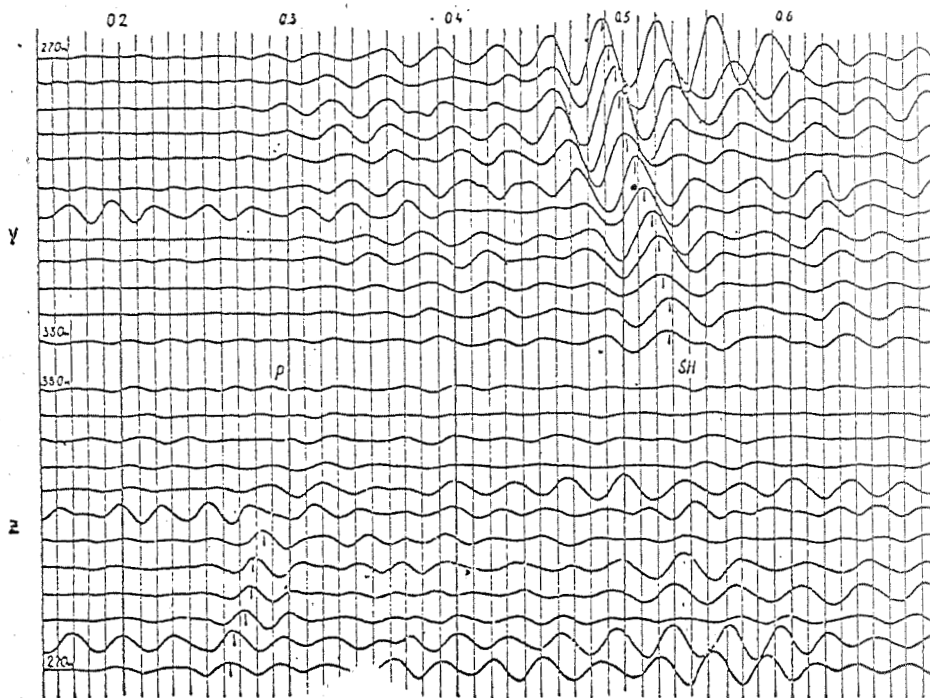


Figure 4. Seismogram illustrating the recording of a transverse SH wave generated by an explosion with stemming (Iskitim region, distance from source 270-380 m, explosion +y, size of charge 60 x 3 g, depth at which charge buried 1.2 m).

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